ULTRASONIC VELOCITY MEASUREMENTS APPLIED TO PROCESS CONTROL OF METAL MATRIX COMPOSITES DENSIFICATION

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INTRODUCTION

Discontinuous metal-matrix composites are emerging as advanced materials for applications requiring high performance isotropic mechanical properties. They offer significant improvement in the mechanical and physical properties over conventional monolithic alloys which can result in significant weight savings. They also have the advantage of tailoring certain properties to meet specific requirements. There are, however, some impediments that adversely limit the use of metal-matrix composites, such as production cost and lack of suitable nondestructive techniques to be applied for the control of processing parameters used in their manufacturing[1]. The control of these parameters will result in the manufacturing of composites with uniform properties and the detection of defects at early stages of processing cycles, which reduce manufacturing cost and enhance productivity.

In the last few years, ultrasonic measurements have been utilized to characterize linear and nonlinear elastic properties of a variety of commercial metal-matrix composites[2,3]. In order to relate NDE measurements to processing conditions we have developed a capability to manufacture Al-SiC composites using a solid state powder metallurgy method followed by cold isostatic pressing and use this facility along with ultrasonic measurements to establish relationships between processing conditions and NDE measurements. These relationships will then be used for the development of models representing processing parameters and properties. In this paper we find a good correlation between ultrasonic velocities and both volume percentage of reinforcements as well as particle sizes. These results give promise to use ultrasonic velocity measurements in the NDE of densification of Al-SiC metal-matrix composites.

EXPERIMENTAL

Materials

Aluminum alloys 1100, 6061and 2124 are used as metal matrix and SiC particles are used as the reinforcement. Average particle sizes(diameter) for the Al alloys are

Table I. Composites and Samples (the numbers immediate before "μm" are the average particle sizes and those in parenthesis are the Al to SiC particle size ratios).

COMPOSITES	SAMPLES		
Al + SiC	Al 95 % (V) SiC 5 % (V)	Al 80 % (V) SiC 20 % (V)	Al 65 % (V) SiC 35 % (V)
Al 1100 10 μm + SiC 74 μm (0.14)	A1	A2	A3
Al 1100 30 μm + SiC 74 μm (0.41)	B1	B2	B3
Al 1100 100 μm + SiC 74 μm (1.35)	C1	C2	C3
Al 1100 10 μm + SiC 10 μm (1.00)	D1	D2	D3
Al 1100 30 μm + SiC 10 μm (3.00)	E1	E2	E3
Al 1100 100 μm + SiC 10 μm (10.0)	F1	F2	F3
Al 6061 20 μm + SiC 74 μm (0.27)	G1	G2	G3
Al 6061 25 μm + SiC 74 μm (0.34)	H1	H2	H3
Al 6061 40 μm + SiC 74 μm (0.54)	I1	I2	I3
Al 6061 20 μm + SiC 10 μm (2.00)	J1	J2	J3
Al 6061 25 μm + SiC 10 μm (2.50)	K1	K2	K3
Al 6061 40 μm + SiC 10 μm (4.00)	L1	L2	L3
Al 2124 10 μm + SiC 74 μm (0.14)	M1	M2	M3
Al 2124 10 μm + SiC 10 μm (1.00)	N1	N2	N3

respectively 10, 30 and 100 μm for Al 1100; 20, 25 and 40 μm for Al 6061; and 10 μm for Al 2124. SiC particles of average sizes(diameters) of 10 and 74 μm are used in this study. SiC particles at volume fraction of 5, 20 and 35 % are mixed with Al alloy particles resulting in three sets of samples. Using various combinations of Al and SiC, 42 samples labeled as in Table I are prepared for ultrasonic measurements.

Processing

Mixed powders are blended well to have homogenous mixture. The mixture is pressed uni-axially up to 207 MPa (30 ksi) using a computer controlled Instron (Universal Testing) Machine in a cylindrical die of 19.05 mm in diameter taking about 6 gm of powder. To have samples with smooth surfaces which are essential for good signals in ultrasonic measurements, the die was polished very well. For smooth release of samples from the die, spray lubricant was applied inside the die before pouring the powders into the die. To get uniform and higher density, the samples were further pressed isostatically in a Cold Isostatic Pressing (CIP) machine at 276 MPa (40 ksi). Final samples were cylindrical in shape, 8 to 10 mm in height and 18 to 19 mm in diameter.

MEASUREMENTS

Density Measurements

Densities of all the samples were calculated from volume and weight measurements. Due to presence of excess porosity Archimedes principle could not be applied for density measurements. In this study the densities of all the samples are calculated using the conventional formula of density, $\rho = m/V$ gm/cc, where m is the mass of the sample in gm and V is the volume of the sample in cubic cm. All the masses are measured using a weighing instrument accurate up to .001 gm. The volumes are calculated from the diameter and height of the samples which are measured with a calipers having a least count of .01 mm. It is noticed that the densities vary in a great extent from sample to sample. The final relative densities obtained from uni-axial pressing vary from 66 to 94 % and it ranges from 70 to 97 % after CIPping[4]. The mixture densities (100 %) are calculated using the rule of mixture (ROM). The densities of monolithic Al alloys and SiC were taken as Al 1100 = 2710 Kg/m^3, Al 6061= 2700 Kg/m^3, Al 2124 =2770 Kg/m^3 and SiC = 3200 Kg/m^3 [5].

Ultrasonic Velocity Measurements

Ultrasonic velocities are closely related to the bulk characteristics of the material elastic constants. To measure these velocities, pulse-echo-overlap technique was applied which is described in detail by K. Salama et al [6]. The measurements were performed at ambient temperature using quartz transducers with center frequency 1 to 5 MHz. The diameter of the transducers were 0.25 and 0.50 inch. Both longitudinal and shear transducers were employed to measure the longitudinal and shear velocities respectively. The transducers were acoustically coupled to the sample by a couplant. This was done to prevent any air medium between the specimen and the transducer, which leads to the attenuation of the signal. The transmitted signal propagate through the specimen in the form of mechanical stress waves and are reflected by the opposite face of the specimen which is picked up by the same transducer. The transducer converts the waves back to radio-frequency voltages which are detected by a broadband receiver. A continuous wave (CW) signal generator coupled to a frequency decade divider is used to generate the repetition rate of the RF pulse oscillator and receiver. This allows the repetition rate to be adjusted so that echoes from a given pulse decay are completely attenuated before the next pulse is introduced. By adjusting the delays and the widths of the strobe generator, a given

Table II. Densities, Ultrasonic Velocities and Elastic Constants for the composites with 5 % SiC.

Sample	Density gm/cc	Relative Density (%)	V_L m/sec	V_T m/sec	E GPa	G GPa
A1	2.62	95.8	6224	3518	102	32.4
B1	2.65	96.9	6313	3510	106	32.7
C1	2.63	96.2	6519	3544	112	33.0
D1	2.59	94.6	6548	3505	111	31.8
E1	2.62	95.7	6753	3664	119	35.2
F1	2.57	94.1	6976	3697	125	35.1
G1	2.49	91.5	6821	3914	116	38.1
H1	2.51	92.0	6754	3883	115	37.8
I1	2.47	90.5	6855	3880	116	37.2
J1	2.44	89.5	6951	3963	118	38.3
K1	2.46	90.4	6807	4013	114	39.6
L1	2.45	90.0	6841	3914	115	38.9
M1	2.44	87.3	6993	3748	119	34.3
N1	2.38	85.3	7096	4020	120	38.5

pair of echoes are overlapped exactly by adjusting the CW generator frequency, f. When complete overlap is achieved, the time-of-flight, Δt, is read from the frequency counter and the ultrasonic velocity is obtained from the following relationship:

$$V = 2dn/\Delta t \quad (1)$$

where d is the length of the specimen and n is an integer such that dn equals the path length difference between the two echoes [7].

Using the method described above, both longitudinal and shear velocities are measured for all the samples along the longitudinal axis. The elastic constants, E and G are calculated using the relationships:

$$E = \rho V_L^2 \quad (2)$$

and

$$G = \rho V_T^2 \quad (3)$$

where ρ is the density of the specimen, V_L and V_T are the longitudinal and shear ultrasonic velocities respectively.

RESULTS AND DISCUSSION

Ultrasonic Velocity

The experimental results are shown in Tables II, III and IV for the composites containing respectively 5, 20 and 35 % of SiC by volume. Using these results, the relationship between the ultrasonic velocities(both longitudinal and shear) and % of SiC reinforcement are plotted in the Figures 1, 2 and 3 for Al 1100, 6061 and 2124 respectively, showing the effect of particle sizes. To avoid agglomeration of data points, only three out of six sets of data are plotted in figures 1 and 2. Two straight lines for the longitudinal

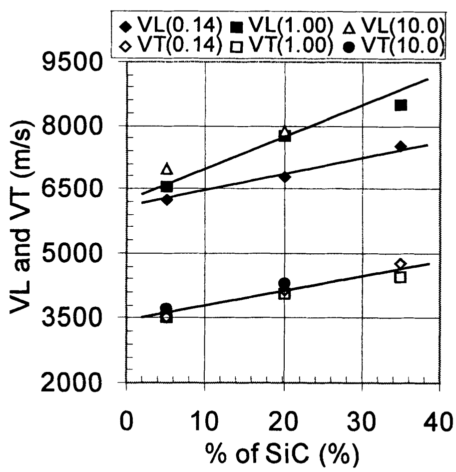

Figure 1. Relationship between Ultrasonic Velocities (V_L and V_T) and SiC content in Al 1100. Bracketed numbers are the Al to SiC particle size ratio.

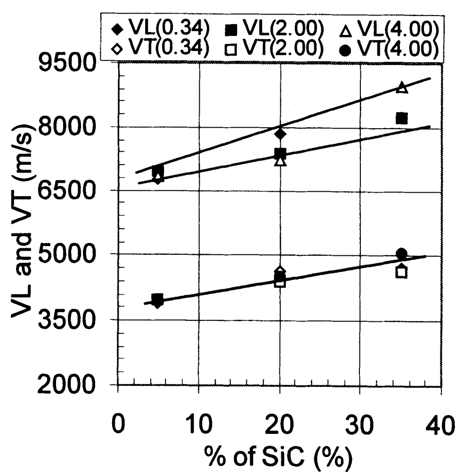

Figure 2. Relationship between Ultrasonic Velocities (V_L and V_T) with SiC content in Al 6061. Bracketed numbers are the Al to SiC particle size ratio.

Table III. Densities, Ultrasonic Velocities and Elastic Constants for the Composites with 20 % SiC.

Sample	Density gm/cc	Relative Density (%)	V_L m/sec	V_T m/sec	E GPa	G GPa
A2	2.64	94.0	6780	4138	121	45.2
B2	2.65	94.2	6768	4249	121	47.8
C2	2.58	91.9	6760	4222	118	46.0
D2	2.44	87.0	7769	4047	147	40.0
E2	2.42	86.1	7822	4102	148	40.7
F2	2.37	84.3	7862	4282	146	43.4
G2	2.47	88.3	7868	4376	153	47.3
H2	2.49	88.9	7848	4634	153	53.5
I2	2.42	86.4	7884	4657	150	52.5
J2	2.30	82.0	7387	4407	126	44.7
K2	2.32	82.8	7286	4646	123	50.1
L2	2.29	81.8	7214	4507	119	46.5
M2	2.44	85.4	6816	4348	113	46.1
N2	2.22	77.6	7546	4432	126	43.6

Table IV. Densities, Ultrasonic Velocities and Elastic Constants for the Composites with 35 % SiC.

Sample	Density gm/cc	Relative Density (%)	V_L m/sec	V_T m/sec	E GPa	G GPa
A3	2.62	91.1	7515	4765	148	59.6
B3	2.62	90.8	8614	4947	194	64.1
C3	2.53	87.6	8967	5198	203	68.2
D3	2.32	80.3	8507	4452	168	45.9
E3	2.25	78.2	8678	4856	170	53.1
F3	N/A	N/A	N/A	N/A	N/A	N/A
G3	2.47	85.9	8223	4547	167	51.0
H3	2.46	85.7	8243	4698	167	54.4
I3	2.40	83.4	8504	4771	174	54.6
J3	2.19	76.2	8223	4635	148	47.1
K3	2.19	76.3	8486	4911	158	52.9
L3	2.17	75.4	8951	5051	174	55.3
M3	2.44	83.5	8296	5057	168	62.4
N3	2.05	70.2	8465	5198	147	55.4

velocities indicate the velocities for lower and higher particle size ratio respectively. It is clear from these figures that both longitudinal and shear ultrasonic velocities increase approximately linearly with the increase of SiC volume fraction in all of the Al alloys which are in good agreement with M. Orrhede [7], D.F. Lee[8], and N. Mourik et al[9]. The slope of the V_L curve is steeper than that of V_T curve. This indicates that the increment in longitudinal velocity is higher than that of shear velocity for a particular increment in SiC reinforcement which is supported by J.H. Shyong et al[10]. A considerable effect of particle size can be observed in longitudinal velocity whereas the effect in shear velocity seems to be small. A clear band from lower to higher particle size ratio is observed in all of the V_L plots. Moreover it is clear from the experimental results as shown in Tables II, III, and IV that the particle size of metal matrix has influence on ultrasonic velocity but the reinforcement volume percentage has a stronger influence.

Elastic Constants

Elastic constants E and G are calculated as described in the previous section which are listed in Tables II, III and IV. The relationships between the elastic constants (E and G) and SiC content are shown in figures 4, 5 and 6 respectively for Al 1100, 6061 and 2124. To avoid agglomeration of data points, three out of six data sets, as shown in the tables, are used to plot the E and G curves for Al 1100 and Al 6061 in figures 4 and 5 respectively. Two straight lines for the E curves indicate the E lines for the lower and higher Al to SiC particle size ratios. From all these figures it is clear that with the increase of SiC content in Al alloys, the values of both the elastic constants increase in approximately linear fashion which are also in agreement with M. Orrhede[7], D.F. Lee[8], N. Mourik et al.[9] and D.F. Lee et al[11]. It is interesting to note that both velocity and elastic constants vary approximately linearly with the increase of SiC content. From the figures and tables it is clear that though ultrasonic velocities increase with the increase of SiC content, the

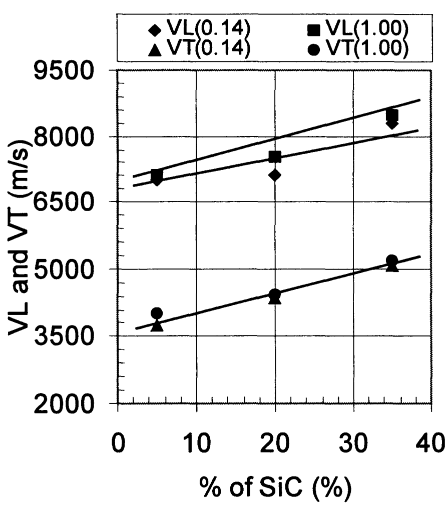

Figure 3. Relationship between Ultrasonic Velocities (V_L and V_T) and SiC content in Al 2124. Bracketed numbers are the Al to SiC particle size ratio.

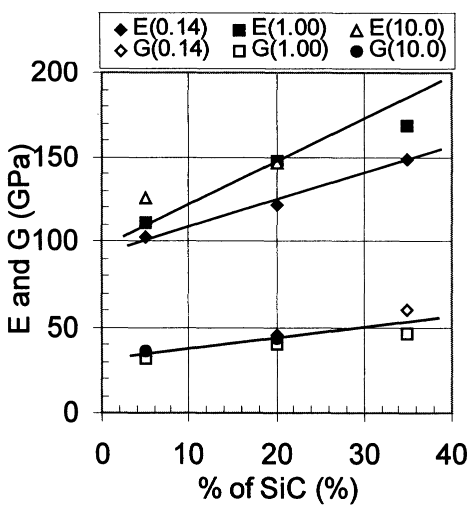

Figure 4. Relationship between Elastic Constants (E and G) and SiC content in Al 1100. Bracketed numbers are the Al to SiC particle size ratio.

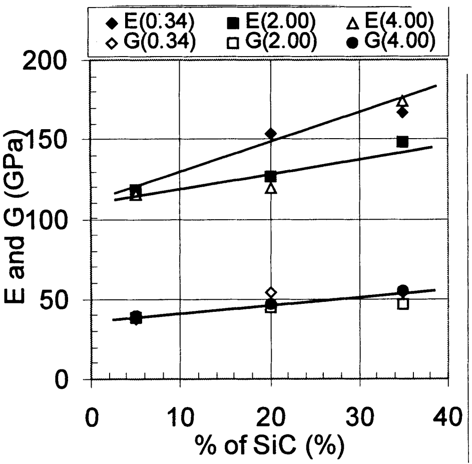

Figure 5. Relationship between Elastic Constants (E and G) and SiC content in Al 6061. Bracketed numbers are the Al to SiC particle size ratio.

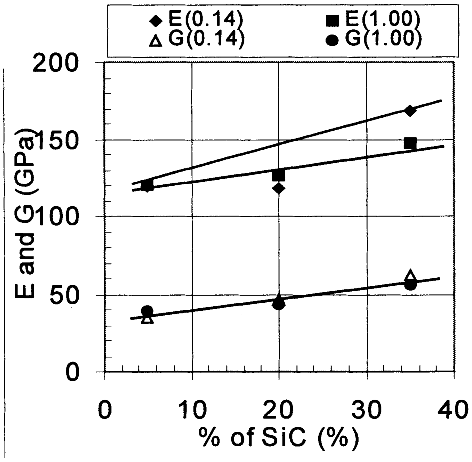

Figure 6. Relationship between Elastic Constants (E and G) and SiC content in Al 2124. Bracketed numbers are the Al to SiC particle size ratio.

densities decrease with the increase of SiC content which is minimizing the effect of velocity increment on elastic constants. It can also be seen that the slope of E curve is steeper than that of G curve, which indicates that the effect of SiC content on E is greater than that on G. Influence of particle size on E is noticeable but the influence of particle size on G seems to be small. A clear wide band from smaller to higher particle size ratio can be observed in Al 1100 for E whereas the same is absent in case of G. Similar patterns are observed in all of the other alloys. It is to be noted here that the higher the Al to SiC particle size ratio the higher the value of E and vice versa for Al 1100. But this pattern seems to be opposite in case of Al 6061 and Al 2124 which is clear in figures 5 and 6. These dissimilarities in E values may be checked out with further experiment. As the particle size ratios used in Al 1100, Al 6061 and Al 2124 are not the same, so it is not possible to make exact comparison between the effect of particle sizes on them. But it is clear that particle sizes play an important role on the densification and the ultrasonic velocities which in turn affect the elastic constants considerably.
The data regarding the particle sizes used in this study were obtained from the supplier of the respective component. This data were verified by the measurements of particle sizes for each of the batches of both the components.

CONCLUSIONS

From the experimental results and discussion shown above, the following conclusions can be drawn:

- Both longitudinal (V_L) and shear (V_T) velocities increase approximately linearly with addition of SiC reinforcement in aluminum matrix.
- Increase in V_L is higher than that in V_T for particular amount of increase in SiC content.
- Particle size has considerable effect on longitudinal velocity and it is absent in shear velocity.
- Longitudinal velocities in Al-SiC composites are lower for smaller Al to SiC particle size ratio and larger for higher ratio.

- ♦ Similar relationships are observed in case of the elastic constants, E and G, respectively as seen in V_L and V_T.

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REFERENCES

1. G.A. Matzkanin, "*Application of NDE for the Process Control of Metal-Matrix Composite Fabrication*", Proc. NDE Applied to Process Control of Composite Fabrication, eds. G.W. Carriveau and D. Chong, NTIAC Publication, p. 245, 1994.
2. B. Grelsson and K. Salama, "*Elastic Constants of Particle and Fiber Reinforced Metal-Matrix Composites*", Res. Nondestructive Evaluation, Vol. 2, p. 83, 1990.
3. M. Mohrbacher and K. Salama, "*Elastic Nonlinearity in Metal-Matrix Composites*". Res. Nondestructive Evaluation, Vol. 3,p. 159, 1991.
4. A.T. El-Sayed, M.H. Rahman, Y.C. Chen and K. Salama, "*Relationship between Elastic Constants and Particle Deformation in Metal-Matrix Composites*", Paper presented in the 25th Annual Review of Progress in QNDE, Snowbird,Utah, July 1998.
5. Metals Handbook, Ninth Edition, Vol. 2, American Society for Metals, 1979.
6. K. Salama and C. K. Ling, "*The Effect of Stress on the Temperature Dependence of Ultrasonic Velocity*", J. Appl. Phys., 51(3), p. 1505, 1980.
7. M. Orrhede, " *Elastic Constants and Thermal Expansion of Aluminum/Silicon Carbide Composites*", Masters Thesis, University of Houston, December 1993.
8. D. F. Lee, "*Ultrasonic Nondestructive Characterization of SiC-Reinforced Aluminum Metal-Matrix Composites*", Masters Thesis, University of Houston, December 1987.
9. N. Mourik, Y. C. Chen and K. Salama, "*Ultrasonic Characterization of Elastic Anisotropy in Aluminum-SiC and –Al_2O_3 Metal-Matrix Composites*", Review of Progress in QNDE, Vol. 16B, p. 1143, 1997.
10. J. H. Shyong, C. T. Gie and C. H. Huang, "*The Nondestructive Characterization of Metal-Matrix Composites*", Proc. The 5th Int'l Conference on Composites Engineering, Las Vegas, Nevada, July 1998.
11. D.F. Lee, K. Salama and E. Schneider, "*Ultrasonic Characterization of SiC-Reinforced Aluminum*", Proc. The 3rd Int'l Symp. on Nondestructive Characterization of Materials, Saarbrucken, Germany, October 1988.